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A technical discussion on microhydropower technology and its turbines

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ABSTRACT

Shortage of electricity supply and other forms of modern energy is serious in most of the developing countries, contributing to low economic and social development. The situation is worse in rural communities, which are often marginalised from grid-based electricity supply because of economic and technical reasons. Currently, development agencies involved in rural power supply in developing countries recommend microhydropower (MHP) as the most robust and reliable source of off-grid power generation. However, in scholarly articles, MHP technology is not popular compared to other renewable energy technologies. This may have contributed to its limited application in off-grid power supply in some countries. Availability of scholarly literature on MHP as the case with wind and solar energies can therefore help to scale-up the level of discourse on the technology among both technical and non-technical stakeholders.

In this paper, the MHP technology has been reviewed in general and the turbines in particular. General description of the technology including challenges and factors for successful implementation of the technology has been given. It has been found that technological issues are among the major challenges and that the turbine is one of the critical technological components of the MHP project. The paper has reviewed common MHP turbines, focusing on their operating principles, merits and demerits with respect to MHP and suitable operating conditions. Factors to consider when selecting suitable turbine for the site and procedure for selecting the turbine have also been outlined in the paper. The paper has been written in a tutorial manner so that the discussions therein, though technical, are shared with stakeholders of different professional backgrounds. It is hoped that the paper provides additional knowledge on MHP technology and in particular on turbines that are used in MHP supply. This can lead to better practical implementation of the technology.

Contents

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1. Introduction

There is shortage of electricity supply and other forms of modern energy in most of the developing countries. Sub-Sahara African region is the worst hit, yet the region is endowed with several resources from which modern forms of energy can be generated, for example hydropower [1]. Lack of capacity to exploit natural resources into modern forms of energy as well as limitations in industrial application of the generated energy may explain the reasons for the shortage of energy supply. In most of the developing countries, shortage of electricity is worse in rural communities who are often marginalised from grid-based electricity supply due to economic and technical reasons. Currently, the requirement for inclusive national economic growth and development has heightened the importance of rural electrification. Rural electrification is achieved through grid extension (on-grid), mini-grid and isolated individual home power systems.

On-grid rural electrification is generally expensive. Sparseness of rural settlements and difficult terrain, in most cases, prohibitively increase the transmission costs of on-grid rural electrification projects. Therefore, it is not a surprise to note that most governments and international development organisations have prioritized on mini-grid and isolated individual home power systems for rural electrification.

In countries with perennial rivers in mountainous topography, microhydropower (MHP) is one of the recommended technologies for rural electrification using mini-grid system, for example in Nepal [2]. Microhydropower technology uses water in a stream that flows through a head to generate power when the water turns a turbine (detailed in Section 2.1). MHP is a well-tested technology and some of the developed nations once relied upon it for power supply before venturing into large-scale hydropower systems. Currently, some emerging economies like China, India and Brazil use the technology to supplement their grid-based electricity supply. In many developing countries, the emergence of energy reform programmes and incentives for promotion of renewable energy technologies has created a favourable environment for development of MHP technology.

1.1. Some advantages and challenges of microhydropower technology

In comparison with solar PV system of the same investment cost, MHP plant is robust to supply diverse power requirements of a typical rural community. The power requirements can be for household, institutional and small-scale industrial purposes. On this basis, international organisations such as Practical Action and United Nations Industrial Development Organisation recommend MHP technology as one of best off-grid electricity supply technologies. MHP is also one of the most efficient, long lasting and reliable forms of renewable energy for electricity generation [3]. For a well-installed and maintained system, the operating life of the MHP plant may reach up to 50 years [4]. Unlike solar PV and wind energy systems, the MHP favours local participation. Practical Action, a charitable organisation that has some involvements in alternative energy supply in developing countries, states that MHP standout as the most adaptable technology to the local conditions and that the technology has great potential for sustainability [5].

MHP is a renewable energy technology because the energy resource ‘falling water’ is replenishable as the fuel (falling water) is part of the hydrological cycle. The MHP project is not associated with significant environmental degradation because of reduced levels of construction activities and negligible capacity of water impoundment. This is one of the major advantages of MHP systems over large-scale hydropower projects. In addition, being a form of renewable energy with no gaseous emissions, MHP systems are among the options for climate change mitigation and therefore, they are candidates for international carbon trading opportunities such as the Clean Development Mechanism.

Previously, the MHP technology was relatively expensive, partly because of its expensive system components like mechanical-hydraulic power governing system, penstock and turbine. Currently, with the advent of low cost electronic load controllers, use of cheap PVC penstocks and availability of low cost turbines, the investment cost of the MHP system has been reduced significantly. With no direct energy cost and minimum maintenance and operation costs, the life cycle cost of MHP are lower than other alternative energy sources such as portable petroleum oil fired electric generators (gensets).

Despite the availability of MHP potential in many developing countries, level of MHP development is still low compared to other renewable energy technologies. Technological challenges are some of the reasons for the underdevelopment of the technology. In the case of sub-Saharan Africa, Klunne [6] observes that lack of ability to locally manufacture critical system components such as turbines is considered is one of the major technological challenges. An increase in availability of technical scholarly literature on MHP technology, as it is with wind and solar energies, can help scale-up the level of discourse on the technology among both technical and non-technical stakeholders. This can help to scale-up the level of MHP development in countries that have the potential.

As already stated, turbine is one of the critical components of the MHP plant. In fact, dissemination of MHP technology is largely centred on the development of low-cost turbines. In addition, choice of turbines can affect economic and technical performance of the MHP project. Development of low-cost turbines have largely been championed by charitable non-governmental organisations, such as the GTZ and Practical Action. To the knowledge of the authors, these organisations are not involved in scholarly publications. In addition, most of the reported studies on microhydropower do not have comprehensive reviews on turbines. As such, technical information on MHP turbines is relatively deficient in scholarly literature. It is important, therefore, to review the MHP turbines to contribute on the existing MHP knowledge.

1.2. Aim and organisation of the paper

The aim of this review paper on microhydropower technology and its turbines is to contribute to an increased level of awareness of the technology through publications. An attempt has been made to present the review in a manner that is suitable even to the audience that does not have relatively enough engineering background. As it is typical for review papers, a considerable amount of literature was sourced from journals, proceedings of conferences and workshops, reports and technical descriptions on turbines from manufacturers. In addition, the authors relied on their expertise and where necessary opinions from other experts were sought to inform on the discussions about the technology and its turbines in particular.

The paper has been organised into four sections, arranged as follows: Section 1 introduces some general issues that trigger microhydropower development. The section also gives the aim of the paper and its organisation. Technology, economic and technology implementation issues are discussed in Section 2. A review on microhydropower turbine and the technical issues to consider when selecting the turbine for a specific site are given in Section 3. Section 4 gives conclusions.

2. Microhydropower overview

2.1. Technology

Microhydropower is another branch of hydropower; distinguished from other branches based on the installed capacity of its plant. MHP plant is in the category of small-scale hydropower projects. There is no consensus on the upper limit for the definition of MHP projects, as can be seen from Table 1. However, the installed capacity of 100 kW seems to be the common upper limit referred in the definition. These definitions have some importance in MHP technology because, in some countries, they serve as the basis for application of subsidies, for example, in the area of rural energy supply.

With reference to Fig. 1, MHP technology is an arrangement of components and structures in which waterpower due to head and flow is converted into mechanical power by a turbine. Most MHP projects generate electricity and in this case, an electric generator becomes one of the critical components to convert mechanical power into electricity. The components and structures of a typical MHP project are grouped into civil structures, generating equipment and transmission system. Civil structures consist of weir, canal, forebay, settling tank, valves, penstock and other associated support structures involved in conveying water to the powerhouse and from the powerhouse to the tailrace water. In addition to guiding water to and from the powerhouse, the system of civil structure also prepares water to be suitable for power generation and controls its flow to the turbine that is located in the powerhouse. The generating equipment is comprised of turbine, electric generator, turbine–generator coupling system and power control system. The transmission system is composed of transformers, wires, electric poles, switches and other associated electrical and electronic components. The function of the transmission system is to transport electricity produced from the generating equipment to the consumption point, also known as load.

Most MHP projects make use of conventional way of harnessing hydropower by virtue of its head and flow (Fig. 1), where water is conveyed in a penstock to the turbine. This is sometimes referred to as 'ducted-turbine' hydropower system. In these systems, hydropower project can either be with a reservoir where a river is dammed or the project can divert a portion of water from the main river to the turbine. The latter hydropower project is known as run-of-river system and is the most common in MHP technology.

Table 1
Different categorisation of small-scale hydropower projects in terms of installed capacity.

Small-scale hydropower categorisation	Installed capacity
Picohydro	Less than 5 kW [7,8]
	Less than 10 kW [4]
Microhydro	Below 20 kW [9]
	Greater than 5 kW but less than 100 kW [10,11,12]
	Up to 100 kW [13]
	Between 10 kW and 200 kW [14]
	Below 500 kW [4]
Mini hydro	Greater than 500 kW but less that 2 MW [4]
Small hydro	Less than 10 MW [15]
	100 kW to 10 MW [13]
	2.5 MW to 25 MW [4]

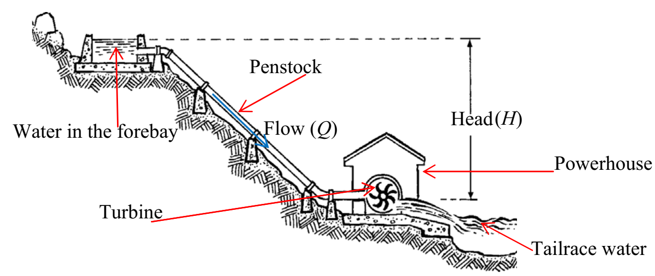

Fig. 1. Schematic sketch showing MHP technology operating on head [16].

Specifically for MHP projects, there is a technology that harnesses hydropower from kinetic energy of the flowing water and the technology does not require presence of head to generate power. This is the hydrokinetic technology. Sometimes, the technology is referred to as zero-head, in-stream, river-current, or ultra-low head hydropower technology. Unlike in the 'ducted-turbine' hydropower system, the turbine in a hydrokinetic hydropower system operates in a free flow condition similar to windpower turbine. Therefore, the potential sites for hydrokinetic MHP plants include sections of fast flowing rivers, irrigation canals and gates of barrages. Although trial versions of hydrokinetic technology have been demonstrated successfully in some developing countries (such as Sudan and Ethiopia) for electricity generation and water pumping, the technology is still not mature.

Just like windpower turbines, the efficiency of hydrokinetic MHP technology is low, being limited by the Betz constant. In addition, hydrokinetic power is sensitive to water flow velocity (it depends on the velocity raised to the power of 3). Therefore, a surge in water flow velocity can cause extensive destruction to the turbine. Research on efficient hydrokinetic turbine runner design and design of support structure against excessive increases in flow velocity is continuing. The hydrokinetic MHP system will not be reviewed in this paper. For the rest of the paper, discussions on MHP technology shall refer to the 'ducted-turbine' system only.

In all hydropower projects, hydropower potential, which is defined as the available power that can be extracted from a site, is a function of head and flow (refer to Fig. 1). Eq. (1) gives this function in a mathematical equation; one of the fundamental equations used in hydropower engineering.

$$P = CQH \quad (1)$$

where P (Watts) is hydropower, Q (m^3/s) is water flow rate, H (m) is the head and C is the product of all other constants (density

of water, acceleration due to gravity and efficiencies of energy conversion processes involved).

These two parameters (head and flow) are important in hydropower engineering, not only for assessment of potential at the site, but also for design and selection of suitable hydropower system for the site. In MHP projects, the most common sources of potential are specific location(*s*) on the course of the river from that have head and flow suitable for the scale of the MHP projects. Therefore, location of the river and identifying the potential sites is one of the important exercises in MHP development. A surveyor, using a map and aerial photographs, can achieve these tasks. The first task, once the potential site has been located, is to measure the catchment area, head and flow. Since head and flow have a direct relationship with power production, they are discussed further in this paper.

2.2. Determination of head and flow

The available (H) head on the hydropower plant is equal to the difference in water levels between water in forebay and tailrace water (refer to Fig. 1). Its measured value depends on the topography of the site and on the location of the powerhouse in relation to the position of the forebay. For MHP system of run-of river type, the requirement to avoid flooding of the generating equipment by locating the powerhouse above the flood level dictates the location of the powerhouse. Determination of head and location of powerhouse is an important exercise in the construction of MHP plants. Usually, head on the estimated is estimated using topographical maps and then confirmed through direct measurements on the site. Methods for measuring head on the site include use of water-filled tube, spirit-level and altimeters instruments.

The flow (Q) is the volume of water passing through the turbine per unit time for power generation. The flow depends on the hydrology of the catchment area, which is influenced by rainfall pattern, temperature and other metrological factors. Flow can be estimated from hydrological records but for the sake of system design, the estimated flow should be confirmed through direct measurement. In practice, the following methods are used to measure flow in a river: using a bucket, float, weir and salt dilution.

Determination of design flow is one of the challenging tasks in the design of a MHP plant. Most of the MHP projects are run-of river type, as already stated. In this case, the design flow can be based on generation of firm power from the site. The design flow can also be based on minimising unit generating cost. In either case, the design flow must take into account the mandatory requirement of environment flow in the river.

For firm power production, the design flow is obtained by taking into account the annual flow pattern of the river, which can be obtained from its flow duration curve (FDC). The FDC shows the percentage of how many days in a year a particular flow is exceeded. For an isolated MHP system where the goal is to produce power almost throughout the year (firm power), a flow which is available 345 days in a year (that is 95% of the year), practically known as Q_{95} of FDC (or firm flow), is selected as a design flow [16].

Microhydropower sites most of the times do not have gauging stations, therefore there are no FDCs for such sites. In such cases, correlations can be used to estimate the flow from nearby gauge stations depending on hydrological characteristics of the catchment area. However, this is more of an academic exercise and can be more risky when data is scarce. For hydropower projects of MHP scale, an alternative is to rely on local inhabitants to obtain a history of minimum flows. The information from the inhabitants is then supplemented with actual measurements on the sites. In tropical countries, minimum flow is usually available in dry season. Again, in the situations where just a small fraction of water is diverted from the major perennial river for hydropower generation, determining design flow using FDC becomes immaterial because the design flow is available throughout the year.

The design flow can also be computed from the FDC but based on minimum unit cost of generating electricity (US$/kW h). The method is explained in the following manner. In ideal cases, as the design flow increases more electricity is generated and hence the unit cost decreases. However, when the design flow is increased further, instances where the turbine cannot generate rated power because the available flow is less than the design flow increase as well. This reduces the capacity factor of the turbine, consequently reducing the amount of electricity that can be generated from the plant; hence increasing the unit generating cost. There is a turning point after which an increase in design flow results in an increase in unit generation cost. This point gives optimum design flow. Mathematical equations can be developed for optimisation of design flow with respect to unit generating cost. However, the determination of design flow basing on this method is rarely used in practice for MHP projects.

Once head has been determined, then it becomes a fixed parameter and hydropower generation at the site becomes a function of flow only. Availability of flow, both of required quantity and quality is important for sustainable operation of a hydropower project. Flow quantity depends on the hydrological-driven run-off, which is currently being affected by global warming and environmental degradation in some tropical countries. Some rivers are no longer perennial due to reduced levels of precipitation and increased levels of water loss in the catchment area. This reduces hydropower generation potential. For planned small-scale hydropower systems of higher capacity, risk assessment should be carried out on future availability of flow, considering the fact that hydropower plant is a long-term investment.

Flow of poor quality, characterised by suspended silt and other solid debris, increases frequency of unplanned plant shut-downs and of maintenance works. Increased levels of siltation in the river can fill up the forebay and choke the generating system. This affects hydropower production of the plant and reduces its operational life. Problems of silt and other solid particles in the flow are serious in MHP plants that are installed on sites where rivers come from a heavily environmentally-degraded catchment area. Incidences of installed MHP being abandoned because of siltation have been reported in some countries like Malawi [17] and Tanzania [18]. In general, sites that experience high frequency of floods and landslides are not suitable for MHP development.

Despite the fact that microhydropower is a technology that does not consume water, its interference with local livelihood such as irrigation can have social problems that can affect performance and sustainability of the MHP project. Such problems can be solved through a good integrated water resource management plan that can facilitate informed water allocation for power production and other water uses such as irrigation. In addition, a possibility of locating the powerhouse so that water for irrigation (and other social uses) is used after power production should be explored during project design stage.

2.3. Economic issues

The MHP system investment cost is composed of survey, project design, civil, generating equipment, electricity transmission and transmission costs. Labour costs during construction, installation and commissioning phases are also included in the investment cost. In general, the investment cost is dependent on many factors such as site condition (topography, remoteness and accessibility), availability of local expertise and duration of project execution time. Bank interests, import duties, and level of MHP penetration may also have indirect influence on the investment cost.

In most developing countries, such as those from sub-Sahara African region, where market penetration of MHP is low, level of

private sector participation in MHP is low or absent, despite having the potential. Where a bank loan is used to finance the project, the investment costs can be very high for initial private owed MHP systems in a country with limited history of MHP projects because of high risks associated with new projects and relatively high interest rates. Therefore, financing of the MHP projects is one of the major barriers in the uptake of the technology. This calls for provision of subsidies to private companies that want to venture into MHP production business. Subsidies have helped to establish a relatively promising MHP private sector participation in Kenya and Rwanda.

Civil cost, consisting of equipment and masonry works is one of the major elements of the investment cost. Civil equipment cost, especially the cost of penstock, depends on MHP site topography. The share of civil works cost component to total investment cost may vary from 20% for a relatively high gradient site and low cost construction project to 60% for a relatively low gradient and expensive construction project [19]. The cost of generating equipment is almost a linear function of its kW size and type [19]. The cost of electricity transmission and transmission lines depend upon the energy density of the load centres and their distances from the powerhouse.

The development of MHP technology in developing countries has been championed by the notion of being one of the least cost options of supplying electricity in off-grid rural communities. For this reason, the design philosophy has been on lowering the system investment cost. With such MHP systems, a compromise on the quality of the installed system is justified on economic reasons. This, to some extent has resulted into MHP being regarded 'appropriate technology' where the involvement of local skills, labour and materials during construction and installation of community-based system is strongly encouraged. However, low cost solutions should not compromise the reliability of the system. A less reliable installation produces low quality electricity, increases maintenance costs and eventually erodes the confidence of stakeholders on the technology.

In situations where profitable use of MHP system is possible or the power system supplies a community that can pay for the generated power, then it is recommended to put up a power system that is constructed following the conventional approach of hydropower plant design that might require imported equipment and skills. The resulting MHP project is expensive but with increased capacity factor, payback period can be relatively short. A high plant capacity factor and a short payback period are attractive conditions for energy supply business. Independent power producers who can sell electricity to the national power utility under the feed-in tariff arrangement can also install MHP projects.

With MHP investment cost depending on several factors, it is not possible to quote a single value that represents a typical investment cost per kilowatt of installed power. The quoted values on investment cost may vary amongst countries or even amongst different places in the same country. Information on investment cost can be sourced from projects that are executed by international implementing agencies and from international consultants. For example, Practical Action reports that from its experience on implementing MHP in Peru, Sri Lanka, Nepal and other countries using local labour and materials, the investment cost ranges from 1500 US$/kW to 3000 US$/kW of installed electric power [5]. Vaidya [20] states that, in Nepal, under the government owned Rural Energy Development Programme, the investment cost of community owned MHP projects ranged from 1279 US$/kW to 1779 US$/kW. In Rwanda, the MHP projects that were promoted by the Energising Development (EnDev) Project funded by Dutch–German Partnership (GIZ) cost between 3000 € and 6000 € (4000 US$ and 8000 US$)/kW [21].

The quoted range of investment cost of MHP using appropriate technology and local labour and materials compare well with investment cost of wind and solar PV energy systems. The investment cost for wind power system is reported to typically range from €1000/kW to €1350/kW (1500 US$/kW to 2000 US $/kW) [22]. According to the International Energy Agency, a typical investment cost of solar PV system ranges from 4000 US$/kW to USD 6000 US$/kW for small-scale applications [23].

Despite availability of measures to reduce the MHP investment cost, the quoted figures of investment cost are still high. In developing countries, costs related to expatriate labour and importation of critical system components constitute a significant share of the investment cost. Therefore, development of local skills in the design, manufacture and installation of critical components of the system like turbine is recommended.

2.4. Technology implementation

MHP technology is designed for a specific site, and the critical component that makes it to be site specific is the turbine. Therefore, in most of the MHP projects, parts and components of turbine system are specific to the installed turbine. This creates problems in sourcing spare parts from off-the-shelf. In most of the times, the spare parts are purchased from the manufacturer of the turbine. Imported spare parts are expensive and may take time to be delivered thereby increasing the plant shut down time. The solution to this challenge is to have standardized parts with which the installed MHP systems can share for a range of design parameters (head and flow). Standardisation improves spare part delivery and therefore, ensures that the plant is available most of the times. This enhances sustainability and usefulness of the projects.

The success of the MHP technology development is manifested through an increase in installations, in confidence level of the installed systems among the developers and in number of productive uses of the generated power. The following are some of the factors to be considered for successful implementation of MHP projects:

- For community owned and maintained project, determine the extent to which the community members are willing to own, use and pay for the generated MHP electricity. Awareness programmes must be conducted before introducing the technology to the community. It is also important to design an inclusive project management structure. It has been found out in Tanzania that involvement of local authorities and central government representatives at local levels in the management structure enhances smooth operations of the MHP projects [18]. If possible, community based MHP projects should be integrated in the rural development programmes for the area.
- If a private MHP project is planned for an off-grid community, then identify potential consumers that can pay for the generated electricity. In most of the sub-Sahara African countries, potential consumers of rural electricity supply are professional and educated personnel that are stationed in rural off-grid areas, business people in rural growth centres and well-to-do rural households. Rural social service institutions like schools, hospitals, police units and other government departments are also potential MHP electricity consumer points. In addition, it is known that provision of electricity in rural areas spurs up business opportunities that can create a further electricity demand.
- There should be technology support structures, such as extension and credit services to support the introduction and development of the MHP technology. Rural technical training centres should be empowered to train local operators and

technicians in the MHP technology and its management. Banks should be encouraged to provide credit services to MHP developers. A public trust or a government agency should be set up to provide collateral services to the banks for those potential developers who may not manage to have collaterals but have viable business proposals to start up independent power production enterprises.

- Develop the capacity to manufacture the critical components of the technology locally. This can be done through training and knowledge sharing in both public and private institutions that are associated with rural energy supply.
- Develop a nationwide reliable and an up-to-date database for MHP resource potential. The database should contain necessary information on topographical and hydrological site characteristics. If possible, the database should also contain suggestions for a possible type of turbines to be installed and the unit cost of generating electricity at the site.

In this section, some technological and economic issues concerning microhydropower technology have been discussed. One of the key elements of the MHP system design is its being sensitive to the site parameters, mainly because of the turbine. In the following section, turbines that are commonly used in MHP technology are reviewed.

3. Microhydropower turbines

A turbine is the 'heart' of any hydropower project because it converts hydraulic power into mechanical power. The turbine is made up of a rotating element (technically known as runner) and a stationary element. Energy conversion process takes place in the runner that is made up of an assembly of blades on a disc. The runner is keyed to a shaft that is supported in the bearings. The shaft transfers mechanical power to a generator for electricity production or to a work-consuming device such as a mill.

It is necessary for manufacturers to evaluate technical performance of the turbines, for example, in form of performance curves. This is because the turbine technical performance is one of the factors to look for when selecting a turbine for the particular MHP site. Turbine performance analysis involves determining its best efficiency point and how the efficiency changes when the turbine operates outside the best efficiency point. Best efficiency point is the operational point, described in terms of runner speed, head and flow, that gives maximum turbine efficiency. Turbine efficiency is evaluated as the ratio of extracted mechanical power to input hydraulic power at the turbine inlet. According to the International Electrotechnical Commission standard number 60193 [24], the turbine efficiency depends mainly on four factors, namely: flow leakage, disc friction, bearing friction and hydraulic loss.

Mechanical power extracted from the shaft is found if the turbine efficiency is multiplied with input hydraulic power at turbine inlet. This mechanical power can be measured at the turbine shaft using a dynamometer or a torque flange. Therefore, turbine efficiency can be evaluated. However, the turbine efficiency cannot describe how well the turbine runner extracts power from the flow. In order to determine this, another efficiency, known as hydraulic efficiency is used. Hydraulic efficiency compares power extracted from the flow by the runner to the input hydraulic power at turbine inlet. Hydraulic efficiency is always greater than turbine efficiency.

Extracted power from the flow is found by making use of Euler turbine equation. The Euler turbine equation gives extracted power as a function of velocities at its inlet and outlet locations and geometry of the runner, with flow properties being constant. The geometric parameters of importance in the Euler equation are the runner blade angle at inlet and outlet, inlet and outlet diameters of the runner.

Hydraulically, the runner is designed by optimising the geometric parameters so that the designed turbine gives maximum hydraulic efficiency. The shape of the runner blade can then be determined. Without going into technical details of runner design, it is necessary to state that blade angles and its shape have significant effect on turbine performance and therefore, care should observed during manufacture and repair works to prevent deformation or any deviations from the original blade design.

While turbine performance has been investigated extensively in large-scale hydropower turbines, little is known about them in scaled-down models, which are used in MHP projects. Small-scale turbines have inferior performance levels compared to large-scale turbines possibly because, as scaled-down models, they experience increased levels of friction because the flow is associated with low values of Reynolds number. Efficiency levels for MHP projects range from 60% to around 85% while large- scale hydropower projects, have efficiency levels of over 90% [4].

There are several examples of turbines used in MHP projects. They are categorised according to their principles of operation and are generally grouped into reaction and impulse types. The turbine principle of operation has a bearing on its suitability for the site, as it will be discussed later in the paper. The next section discusses the technologies and applications of the commonly used turbines in MHP projects. First, their principles of operation are discussed.

3.1. *Reaction turbines*

In reaction turbines, both pressure and velocity energies are extracted from the flowing water and then converted into shaft-power by the runner. The reaction turbine has guidevanes (also called wicket gates), not only to control the amount and direction of the flow, but also to act as nozzles to increase fluid velocity before water enters the runner blades. As the energy conversion process takes place, there is a drop in pressure. Due to pressure drop in the flow, reaction turbine runners are highly susceptible to cavitation [25].

Because of energy conversion due to pressure, a reaction turbine runner must always be filled with water. This calls for careful design of seals, runner blades and careful fabrication of turbine housing casing. High values of static and transient pressures can exacerbate the leakage problem as well as cause structural damage to the runner and its casing. The properties, like tensile strength, of material for the runner and the housing have limitations to withstand certain pressure levels (stresses). Therefore, the reaction turbines are suitable for low to medium heads with high flow rates.

Most reaction turbines have draft tubes (diffusers) that are attached to the runner outlet through which flow is discharged to the tailrace. The draft tube slows down the discharged flow, converting some residual kinetic energy into a positive suction head, thereby increasing the effective head across the turbine. This increases the amount of power output, hence the turbine overall efficiency. The loss, which would have come from a reduction in head as a result of installing the turbine above flood water level can be compensated through making use of a draft tube. Despite the advantage, there are challenges of cavitation, flow separation and whirling in the draft tube due to the suction effect and changes in flow geometry.

Basing on the flow direction in the runner in relation to the axis of rotation, reaction turbines can be radial, axial or mixed flow machines. Common examples of reaction turbines used in MHP projects are Francis, Kaplan, Propeller and Pump-as-turbine. These turbines are briefly discussed in the following sub-sections.

3.1.1. Francis turbines

Francis turbine is basically a radial flow machine, where water enters the runner through the outer periphery in the radial direction and leaves in the axial direction (Fig. 2a). Sometimes, the turbine can combine both radial and axial flow concepts; in this case, it is known as a mixed-flow Francis machine. Francis turbine can be of a vertical axis type (Fig. 2a) or horizontal axis type (Fig. 2b). The vertical axis has an advantage in that it keeps water away from the coupled generator and is economical with powerhouse space. Francis turbines can be set in an open flume or attached to a penstock.

Francis turbines can be applied within the range of 10–50 m (with spiral casing) as medium head plants and less than 10 m as low head plants (with open flume) [4]. In terms of flow rates, Francis turbine can be applied from 0.4 m^3/s to 20 m^3/s [28]. There are numerous potential MHP sites suitable for installation of Francis turbines. However, the complex shape of the runner and steel spiral casing make these turbines expensive to manufacture for low cost MHP projects. In addition, they are not suitable for poor water quality conditions. Francis turbines exhibit a peak efficiency curve, indicating that it performs poorly during part flow conditions. Below 40% of the rated flow rate, Francis turbines may show instability resulting in vibration and mechanical shock [15]. Francis turbines are therefore, suitable for constant flow conditions.

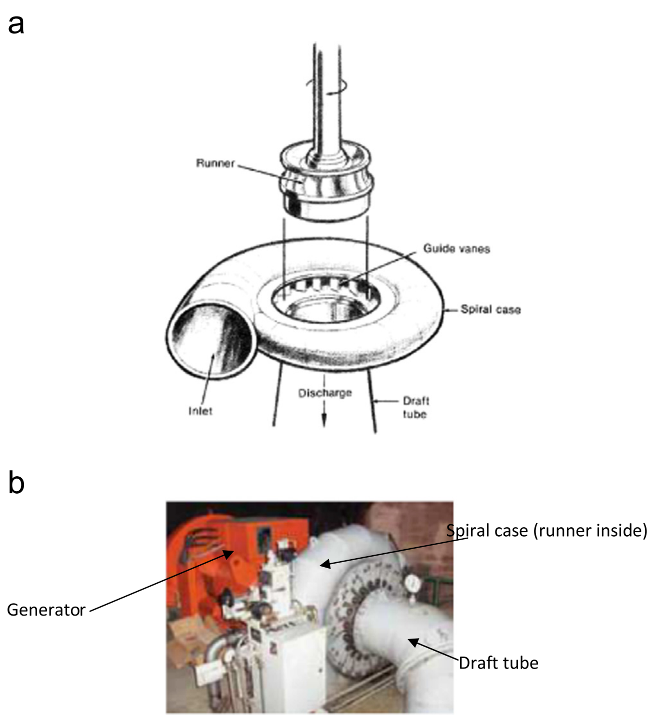

Fig. 2. (a) A general pictorial diagram of the vertical axis Francis Turbine [26]. (b) A horizontal axis Francis turbine installed in the 500 kW Mantsonyane small hydropower station in Lesotho, Southern Africa [27].

3.1.2. Kaplan turbines

For very low head sites, flow direction in the reaction turbine runner has to be more axial for best turbine performance results. Kaplan turbine runner (Fig. 3a) is a typical axial flow machine in which runner blades and guidevanes or both can be made adjustable. If both runner blades and guidevanes are made adjustable the Kaplan turbine is described as double-regulated turbine. The double regulation makes it possible, at any time, for the runner to adapt to any head and discharge variation. A double regulated Kaplan turbine (Fig. 3b) is therefore flexible and can work optimally between 15% and 100% of the maximum design flow [15]. A double regulated Kaplan turbine is also known as a 'full-Kaplan'.

The Kaplan turbine can also be regulated by either fixing blades or guidevanes; but not both of them at the same time. This is known as single regulation. In the case of MHP projects, blades are fixed and such single-regulated Kaplan turbines are less flexible in the case of large head variation. They can work optimally between 30% and 100% of the maximum design flow [15] and are mostly used in small head hydropower plants. A single-regulated Kaplan turbine is also known as a semi-Kaplan.

With adjustable blades, it is possible to control and therefore to decrease incidence losses at the inlet of the runner as the runner rotates [29]. As a result, during part flow operating conditions, the efficiency of double-regulated Kaplan turbine is higher than that of the Francis turbine. However, this arrangement of adjusting blades is more applicable to large-scale hydropower projects than MHP systems because of increased manufacturing and operating costs. In addition, Kaplan turbines, which are suitable for low head sites require large volumes of flow to generate meaningful power. This results in relatively large sizes of intakes and conduits, which significantly increase costs related to civil structures. This makes MHP plant with a low head Kaplan turbine a relatively expensive project. Therefore, research on development of low cost Kaplan turbines for MHP technology should be considered.

Generally, Kaplan turbines are suitable on sites with heads ranging from 2 m to 50 m [15,30]. The amounts of required flow rates are relatively high, ranging from 1 m^3/s to 60 m^3/s [30]. These values are quoted from manufacturers and may not limit the

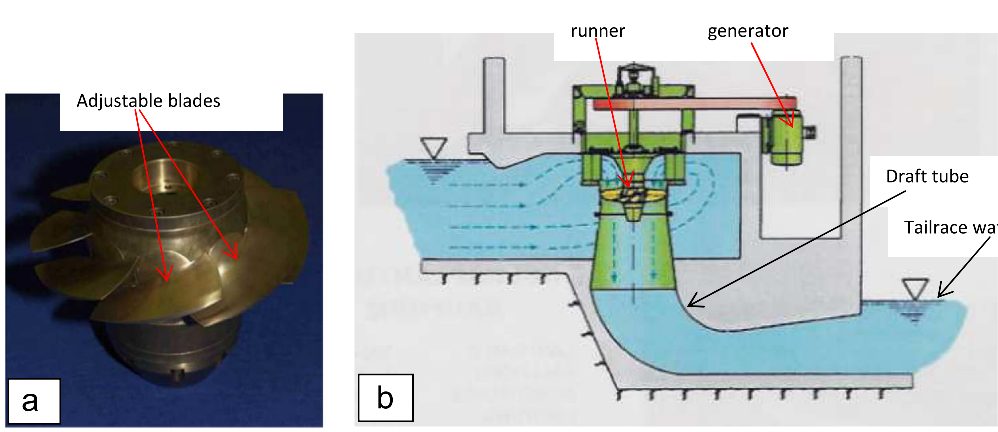

Fig. 3. (a) Kaplan turbine runner; (b) cross-section of a double regulated Kaplan turbine [15].

range of suitability in terms of head and flow. Kaplan turbines are thus, applied in most varied head and flow conditions, therefore, are suitable for numerous MHP sites.

3.1.3. Propeller turbines

A propeller turbine is technically a fixed blade Kaplan turbine. Because of having fixed blades, it is not possible to control losses and the turbine has a peak efficiency curve indicating poor efficiency during part flow conditions. Propeller turbines are therefore, not recommended for MHP sites where flow varies significantly. They have an advantage of simplicity of construction as compared to the Kaplan turbines. For MHP projects, the fixed-blade propeller can simply be encased in a section of the penstock. The propeller turbines used in hydropower projects can have up to 6 blades [31].

Propeller turbines are typically applied in extremely low head sites with large flows because of their high specific speeds. The high specific speed makes direct coupling of the turbine to the generator possible (refer to Fig. 4). This reduces some costs related to shaftpower transmission system. Therefore, for unit power generation, Propeller turbines can be less expensive compared to Kaplan turbines. Considering that there are numerous low head MHP sites, significance of propeller turbines in MHP development is evident.

3.1.4. Pump-as-turbines

In turbomachinery, energy transfer process takes place continuously due to the dynamic action of the fluid that flows through the rotating element. Therefore, it is possible for the turbomachines to be used in reverse. In this case, a centrifugal pump can be used as a turbine, known as pump-as-turbine (PAT) (refer to Fig. 5). However, there are some important points to reflect on before selecting a pump to be used as a turbine because the design philosophy of a pump and turbine are different. A pump is power consumer, designed to produce head and/or flow while the turbine is designed to produce shaftpower. An understanding of the difference in design philosophy can help to get some insights on the performance behaviour of PATs.

A pump has a decelerated flow in impeller and volute because hydraulic energy is converted into head. Decelerated flow is sensitive to flow separation and formation of eddies. To mitigate the occurrence of these poor flow conditions, the impeller passages are made of relatively long blades with increasing cross-sectional area that increases frictional losses. While in turbines, to generate power, the flow is accelerated and is therefore subjected to less turbulence. The turbine runner passages are therefore relatively short that reduces friction losses. Thus, the turbine has high efficiency levels compared to a pump.

During the design of centrifugal pumps, to avoid instability during operation, the impeller blades are curved backward in relation to direction of rotation of the runner. If the pump is to be used in the turbine mode, where the flow has to change direction, the blades become oriented in 'curved forward' with respect to the direction of rotation of the runner. The latter situation induces instabilities. In large-scale hydropower, PATs have special blades that are a combination of backward and forward profiles to mitigate instabilities in the machine when it is used in both applications (pumping and turbining). In MHP system, a simple centrifugal pump with backward curved blades is often used as a turbine.

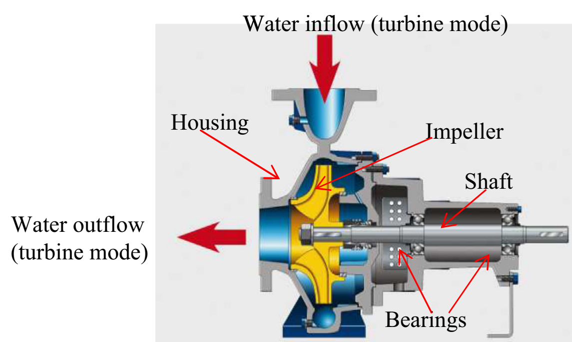

Fig. 5. Cut-view of Pump-as-turbine showing impeller and direction of water flow [32].

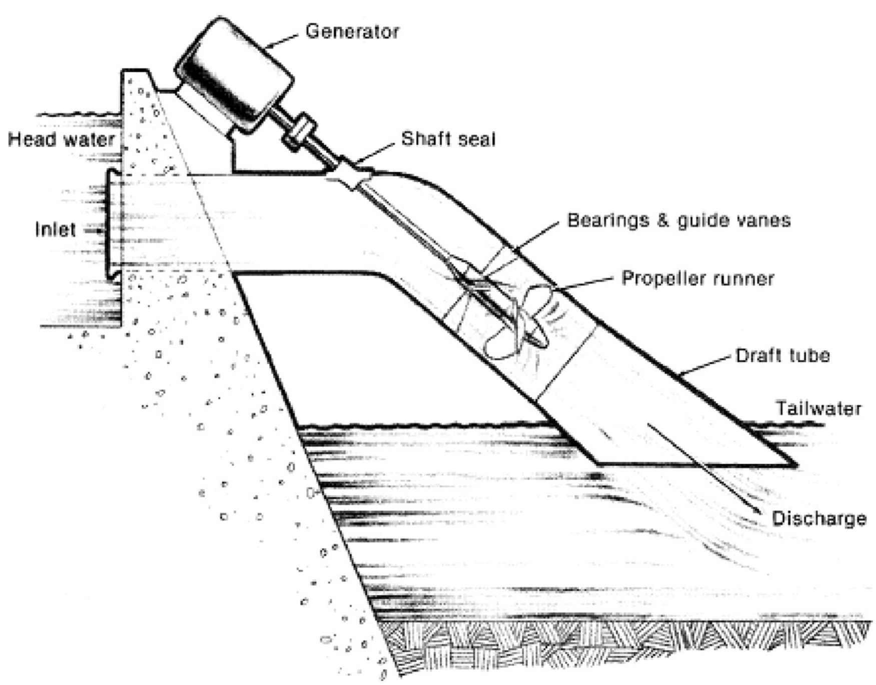

Fig. 4. MHP diagram showing propeller turbine [26].

The optimum flow and head in the turbine mode is always greater than in pumping mode because of hydraulic losses. When operating at the best efficiency point (BEP) in the pump mode (actual pump), an output head is reduced by hydraulic losses. The pressure head required on the machine to operate at the same BEP must be increased by the hydraulic losses when the machine operates at the same speed in the turbine mode. Therefore, the maximum efficiency of the turbine mode always shifts towards the higher flow rate than in the pump mode. Thus, to achieve an efficient operation of a PAT, the operating head and flow-rate must be increased over the rated pump head and flow-rate. Therefore, the BEP in pumping and turbining modes are different for the same machine.

To select the PAT for a particular MHP site, therefore, there is a need for information on performance characteristics of the centrifugal pump operating in the turbine mode. However, pump manufacturers do not provide performance characteristic curves in the turbine mode. Lack of PAT performance data is stated as one of the significant challenges in the design of PAT for a MHP site [33]. There is therefore, a need to estimate the performance of the PAT to get useful design data. The best method is to test the pump in the turbine mode and generate its performance characteristics. However, this method is expensive and not practical for MHP projects.

Alternatively, the PAT performance can be predicted from BEP of the pump using empirical correlations. However, reliability of empirical correlations is low; different correlations are found to give different results for the same flow conditions [26,34,35]. It is therefore recommended to use the mean of at least three different correlation equations, whose predicted BEP converge to a certain tolerance, in order to make a reliable decision on selecting the PAT for the site.

Literature by Williams [36] provides a good background on the available correlations. The correlation proposed by Sharma [37] is recommended to give reliable results. Eqs. (2) and (3) are the Sharma correlations, as reported in Williams [36].

$$Q_t = \frac{Q_{bep}}{\eta_{max}^{0.8}} \tag{2}$$

$$H_t = \frac{H_{bep}}{\eta_{max}^{1.2}} \tag{3}$$

where Q_t (m^3/s) and H_t (m) are the flow rate and head at the BEP for the turbine, respectively. Q_{beb} (m^3/s) and H_{bep} (m) are the flow rate and head at the BEP for the pump respectively at maximum efficiency, η_{max}. The pump's BEP can be obtained from its performance chart that is usually supplied by the manufacturer.

Apart from laboratory tests and correlations, another method use knowledge of the pump geometry for predicting the performance of the PAT. This method was proposed by Burton and Williams [38] and is known as the area-ratio method. However, the area-ratio method is complicated and unreliable as well.

The main drawback of simple PAT is its inability to regulate flow because simple centrifugal pumps do not have guidevanes in the impeller casing as the case with purpose-built turbines. The PATs therefore, are suitable in constant flow conditions. Absence of guidevanes in simple centrifugal pumps makes governing of PAT by controlling flow not possible. Flow in the turbine mode enters the PAT in axial direction and leaves in the radial direction around the periphery of the runner. Therefore, development of a flow regulating system to be retrofitted into the simple centrifugal pump is one of the improvement that can be made on PAT.

Due to regulation problems and poor performance of PAT during part flow condition, the PAT are designed to be operated at one point: the full flow condition. In low flow conditions, it is still possible to use the PAT at full flow but intermittently using the 'siphon intake' technology that is described by Williams [39]. The 'siphon intake' system, allows the reservoir to accumulate low flow before it discharges the flow into the penstock for power production. Thus, the 'siphon intake' produces intermittent power. The intermitted power is unsuitable in some engineering applications that involve powering machinery that require active power like motors but can be used in other applications like battery charging, ice making and heating.

In increased flow conditions, it is not possible to increase the output from PAT because the designed constant flow is the maximum capacity that the system can hold. Therefore, to make maximum use of the MHP potential, second or subsequent PATs can be installed to make use of the increased flow. However, this choice should be evaluated against additional costs that may outweigh the economic advantage of using PAT system instead of using a single purpose-built turbine.

PATs have some advantages over the purpose-built turbines that are used in MHP projects. The electric powered centrifugal pumps come together with motors, already assembled into a unit. Such PAT units can easily be retrofitted to generate MHP from potential sites such as water supply systems, irrigation water systems, barrages and other water structures. Mass production of centrifugal pumps can reduce unit cost of the pump, which can make PAT economically attractive. In addition, with constant flow, PAT makes it convenient to use cheap Electronic Load Controllers (ELCs) to govern power output.

Centrifugal pump units are available in already standardised form in several sizes, and their spare parts are readily available. This makes PATs convenient for modularisation, which an important requirement for MHP development. Centrifugal pumps and their parts have a short delivery time since they can be bought off-the shelf. In addition, MHP projects with PAT are relatively easy to install since they use standardised pipe fittings. Finally, centrifugal pumps are relatively simple turbomachines and are commonly available even in developing countries. Therefore, PATs are some of the most recommended turbines for MHP development in developing countries.

PATs are suitable in sites that have heads ranging from 15 m to 100 m and flow rates from 0.005 m^3/s to 0.05 m^3/s [35]. In sites with very small heads, of less than 5 m and flow 0.05 m^3/s to 0.1 m^3/s, axial PAT are recommended instead of centrifugal pumps [35]. In cases where head is relatively high, a system of multistage pumps can be used as PAT. However, research is needed to explore system performance and economic viability in cases where a system of pumps is used as a turbine. For further information on PAT technology and design, the interested reader is recommended to consult literature by Gopalakrishnan [34] and Williams [39].

3.2. Impulse turbines

In impulse turbines, hydraulic energy is first converted into kinetic energy in form of free water jet by nozzles. The water jet impacts the runner blades and due to change of momentum of the jet, a force is created on the runner blades that makes the turbine rotate. The pressure across the runner of the impulse turbine is essentially constant at atmospheric pressure. The runner is not submerged in water and thus, the turbine casing serves to guard against water splashing, lead flow to the tailrace water and safeguard against accidents. Therefore, careful fabrication of the casing is not critical in an impulse turbine as compared to a reaction turbine, which results in reduced manufacturing costs.

Impulse turbines possess some economic advantages over reaction turbines because they do not require special pressure casing, pressure relief valves, special pressure seals and bearings. In addition, they are favoured in poor water quality conditions because they are not sensitive to water quality as the case with

reaction turbine. Ideally, impulse turbine is not associated with cavitation because energy transfer takes place at a constant atmospheric pressure, as already stated. The major disadvantage of impulse turbines is that they are unsuitable for low-head sites because of their low specific speeds. Common examples of impulse turbines applied in MHP projects include Pelton, Turgo and Crossflow. These turbines are discussed in the following subsections.

3.2.1. Pelton turbines

Pelton turbine is a free jet turbine, invented around 1880 by an American Engineer, Pelton, after whom it is named [40]. In a Pelton turbine, one or more jets impinge buckets that are set around the periphery of a rim (refer to Fig. 6a). The jet hits each bucket and is split into half by a ridge, so that each half is turned and deflected back through an angle of nearly 180° for maximum power production (refer to Fig. 6b). The jet (flow) is controlled by a needle valve (refer to Fig. 6b) that adjusts the flow through the nozzle to the turbine runner. The axes of the nozzles are in the plane of the runner. The nozzle has a deflector to deflect the jet from the runner. This is done to give time to close the needle valve to avoid excessive pressure transients in the flow system during cases of abrupt load rejection on the generator.

A basic theory on performance of Pelton turbine shows that the best efficiency occurs when the runner is rotating at a periphery speed that is equal to half the speed of the jet. The flow rate the turbine can admit (hence power) is limited by the interference between the jet leaving the bucket and the incoming jet from the nozzle. Harvey et al. [41] state that the jet must be deflected through 165% in order to prevent the discharged jet from interfering with the oncoming jet. During operation, the efficiency of Pelton turbine is also limited by windage losses due to water splashing in the casing.

Pelton turbines have high efficiency levels and good load regulation capabilities. Those Pelton turbines with multiple nozzles have superior performance during part-flow conditions than single nozzle turbines. For example, the efficiency of a Pelton turbine is good from 30% to 100% of the maximum flow for a single nozzle turbine and from 10% to 100% for a multi-nozzle runner [15]. However, Pelton turbines must be placed above tailrace water level to keep the runner clear of water and in so doing, some amount of the available head at the site is lost which may be significant for some MHP projects.

In MHP projects, Pelton turbines can effectively be used for medium heads of about 10 m to 50 m [4] and would therefore require relatively less flow to generate the required power. For high head installations, constraints concerning penstock failure due to high static pressure could limit use of cheap PVC pipe and would therefore make MHP investment cost relatively high if steel or concrete penstocks are used instead. Pelton turbines are not recommended for very low heads because their rotational speeds could become low and the resulting runner sizes would correspondingly become large and unwieldy.

3.2.2. Turgo turbines

Turgo turbine is a compact impulse turbine invented by Gilbert Gilkes in 1919 [42] and his company (Gilbert Gilkes and Gordon Limited) is one of the few companies that currently manufactures the turbine. Just like Pelton turbine, Turgo turbine may have multi-nozzle injectors to optimize its efficiency and performance. The nozzle-injector size is fixed and up to four nozzles can be used [43]. Though some companies manufacture this turbine, published data on Turgo turbine design and its performance are few and earlier technical discussions on the turbine have often been lumped together with Pelton turbines. In terms of performance characteristics, Turgo and Pelton turbines appear to be similar. Cobb and Sharp [44] experimentally found out that Turgo turbine

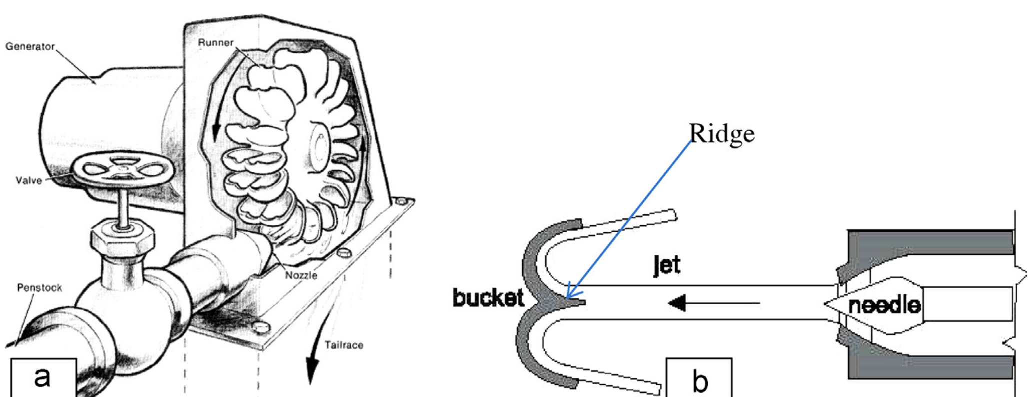

Fig. 6. (a) Pictorial sketch of a small scale Pelton Turbine for use in MHP technology [4]. (b) Schematic sketch showing basic functioning of a Pelton turbine [15].

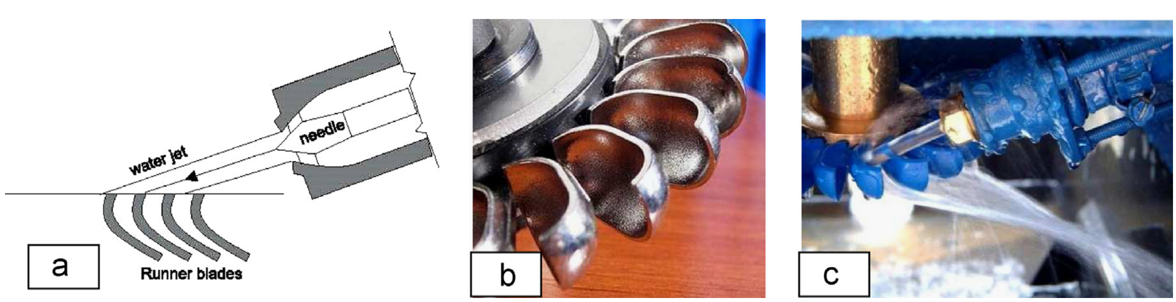

Fig. 7. (a) A schematic sketch showing basic principle of a Turgo turbine [15]. (b) A picture showing buckets of Turgo turbine mounted on the rim [42]. (c) A picture showing jet striking the bucket and leaving the bucket [42].

optimum efficiency occurs when its speed ratio (runner peripheral velocity divided by jet velocity) is 0.46, similar to that of Pelton turbine. Lately, Anagnostopoulos and Papantonis [45] have successfully demonstrated the possibility of design optimization of the Turgo turbine using numerical analysis, as the case with Pelton turbine.

Turgo turbine (refer to Fig. 7b) is similar to the Pelton turbine only that the jet is designed to enter the plane of the runner rotation at an angle (refer to Fig. 7a), typically 20 degrees [4], so that the jet enters the runner on one side and exits on the other side (refer to Fig. 7c). Because of this design arrangement, there is no interference between the discharged jet and the oncoming jet. As a result, Turgo turbines can handle large amounts of flow rates than equivalent sizes of Pelton turbines. As such, they can attain higher speeds than Pelton turbines. Further, because of the capacity to handle larger flow rates, the Turgo turbine has a smaller runner diameter than a Pelton turbine for unit power output.

The resulting high runner speed of the Turgo turbine makes it possible for direct coupling of turbine and generator in MHP projects. In addition, it is also possible to have the turbine-generator unit with all accessories, which is convenient for modularized MHP projects. This reduces investment cost, improves overall efficiency and reduces maintenance cost. An example of a compact design is the Gilkes latest (2005) design that can be applied within the head range of 40–150 m, flow range of 0.050–0.250 m^3/s and power output from 30 kW to 200 kW [46].

In general, Turgo turbines can effectively be applied over a range of site conditions with heads ranging from 15 m to 300 m [45]. This puts them in the category of medium to high head turbines. Turgo turbines can be used as an alternative to other turbines (such as single jet Pelton and high head Francis), in the case of large flow variations because they have a flat efficiency curve, which indicates optimum performance during part-flow conditions [47]. Despite advantages to small-scale hydropower applications, Turgo turbines are seldom applied in MHP projects and very few companies manufacture it, as already stated. Anagnostopoulos and Papantonis [45] state that this is partly due to the complexity of the runner that makes manufacturing difficult and expensive for MHP projects.

3.2.3. Crossflow turbines

Crossflow turbines are among the simplest turbines to design and manufacture and for this reason they are widely applied for MHP supply in some developing countries, especially in Asia. The turbine is composed of runner, nozzle and housing (refer to Fig. 8b). For low cost projects, the runner is simply a squirrel-cage-shaped device that is made of two or more circular discs joined by curved horizontal blades. The runner can be fabricated in a standard workshop without requiring sophisticated tools. The runner blades can be cut from a standard steel pipe and then welded onto the discs (refer to Fig. 8b). The nozzle, apart from issuing water jet, also directs and regulates flow (jet) into the runner using the guidevane. Some other versions of the turbine do not have a guidevane, but instead the variable nozzle controls the amount of flow into the turbine.

Crossflow turbine obtains its name from the nature of jet flow in the runner. The flow crosses the runner blades transversely (hence 'Crossflow'), thereby exchanging energy with the runner in two distinct stages before the flow is discharged (refer to Fig. 8a). The original turbine design was based on pure impulse principle where a gap was left between the nozzle and runner housing. The gap makes sure that the jet enters the runner at atmospheric pressure. However, recent improvements on the turbine where the nozzle is joined to the runner housing and the housing follows the runner closely has resulted in the jet having a positive pressure when entering the runner [50].

Crossflow turbine is reported to have been invented by an Australian Engineer, Anthony Mitchell, who patented the original design in 1903 [51]. It is also reported that a Hungarian mechanical engineer, Professor Donat Banki refined and disseminated it through series of experiments between 1916 and 1918 in West Germany [51]. JLA & Co. Limited [52] states that by 1920, the turbine was well known in Europe, may be because of Prof. Banki's publications on the turbine. It is further reported that a German civil engineer, Fritz Ossberger, collaborated with Mitchell and worked on the development of the turbine. In 1933, Ossberger obtained the German Imperial patent for the turbine [49]. Therefore, it is convenient to state that Mitchell, Banki and Ossberger played important roles in developing the Crossflow turbine technology. This explains why the Crossflow turbine is also known as Mitchell or Banki or Ossberger turbine or a combination of their names.

The classic Crossflow turbine unit has undergone some modifications; one of the remarkable modifications is the addition of the draft-tube to the runner by Cink, a Czech Engineer [53]. The other modification concerns its simplification so that it can be used as a low cost turbine, which can be locally in developing countries with limited workshop tools. The first known international organisation to be involved in the development of low cost versions of Crossflow turbines that can be locally manufactured is the Swiss Centre for Appropriate Technology (SKAT) (such as the T3, T5, and T7 Crossflow turbine versions). The SKAT low cost Crossflow turbine versions were successfully installed in Nepal. Later, they were introduced to other developing countries such as Sri Lanka, Peru and Indonesia [4]. International organisations like SKAT, German Technical Operation

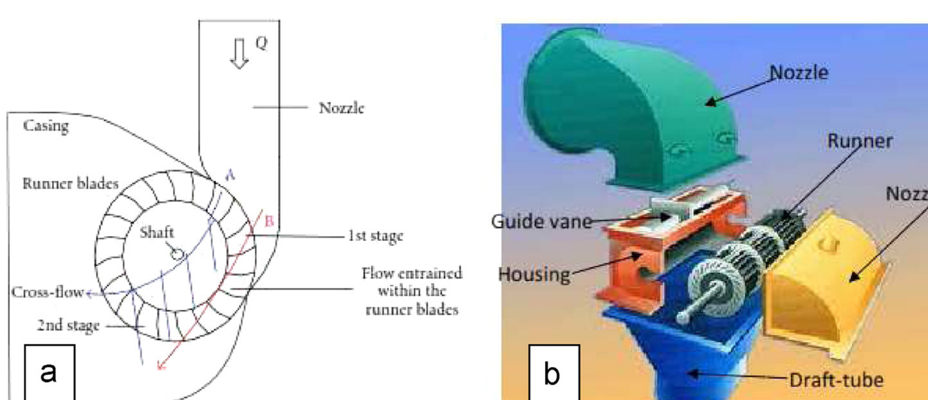

Fig. 8. (a) A typical schematic view of Crossflow Turbine nozzle and runner also showing flow distribution in the runner [48]. (b) A typical exploded view of a Crossflow Turbine with multiple runners mounted on the same shaft [49].

Agency (GTZ), and Intermediate Technology Organisation (currently known as Practical Action) have played an important role in disseminating the low cost versions of Crossflow turbine in developing countries.

The main area of concern for Crossflow turbine is its low performance levels compared to other turbines used in MHP projects. This has contributed to the turbine not being very much promoted by many small-scale turbine manufacturers. According to Mockmore and Merryfield [54], who translated the original Crossflow turbine invention publication, the maximum theoretical efficiency of the turbine is 87.8%. Upon testing the turbine model, Mockmore and Merryfield [54], obtained a turbine efficiency of 68%. This called for performance improvement on the turbine, and Crossflow turbine has since been subjected to several laboratory based performance improvement studies to optimise its geometric design parameters.

Despite having low performance levels, Crossflow turbine is recommended in a varied flow condition because of its flat performance curve. This positive aspect of the turbine makes it possible to harness maximum hydropower from the varied flow MHP site. Therefore, technically, it is possible for the Crossflow turbine to compare favourably with other turbines on an annual capacity factor basis despite having low performance levels.

Crossflow turbines can be applied in low and medium head sites with diverse range of flow rates than any other conventional turbines used in MHP technology. Further, the runner can be manufactured and operated in a multi-cell arrangement where the cells (individual runners) are connected on the same shaft. This arrangement is recommended for modularisation. In addition, apart from being of low cost, the turbine has a safe cleaning effect where it does not become clogged of debris during operation. This is a positive factor in situations where the users do not have enough technical skills and capacity to dismantle and clean the turbine runner.

3.3. Selecting the turbine for the site

Hydropower potential at the proposed sites may be the same but the suitable turbine to be installed at may be different because the turbine is selected according to site conditions and runner speed of rotation. The turbine specific speed, usually written as N_s, is the criterion that is used when selecting the optimum type and form of the turbine for a particular site. The turbine will not operate optimally if its form does not match with the site conditions. The turbine specific speed, defined as the speed of a geometrically similar turbine that would develop unit power when working under a unit head, can be calculated from Eq. (4). Theoretically, all geometrically similar turbines operating at their respective optimum design conditions have the same value of N_s. Practically, geometrically similar turbines are specified within a given a range of N_S.

$$N_s = N\frac{\sqrt{P}}{H^{1.25}} \tag{4}$$

where H (m), N (rpm) and P (kW) are head, rotational speed and power output, respectively.

Specific speed, N_s is a 'dimension' parameter and therefore, system of units must be observed. In English units, rotational speed N is in revolutions per minute, power output is in horsepower and head is given in feet. In some cases, a dimensionless number, known as speed number, symbol Ω, is used instead of specific speed. Speed number is related to speed number by $N_s = 89\ \Omega$ (N_s calculated using Metric units). This relationship is obtained from the derivation of the speed number according to its definition.

Practically, selection of the turbine for a particular site can be an iterative process since the turbine output power and rotational speed are not yet determined. Therefore, the first step is to establish the net head and design flow from the site. The 'envelopes' from manufactures that recommend various turbine types according to head and flow can be used to initially guide the choice of the type of a turbine to select (for example Fig. 9). It is likely that envelopes can overlap at a particular design point of head and flow. In such cases, other criteria should be used to select the turbine type. This process depends on the experience of the turbine installer, but some factors are suggested here to aid in the decision making during selection. These factors are given as follows:

(i) Investment cost of the turbine unit has to be looked into because some turbines are expensive. In general, impulse turbines are less expensive compared to reaction turbines. Crossflow turbines are the least expensive. It should be born in mind that the type of turbine also affects civil costs. As discussed already, reaction turbines such as Propeller and Kaplan require significant sizes of flow conduits to handle large flow hence MHP projects with these turbines are associated with increased investment costs.

(ii) Complexity of the turbine in relation to the availability of local manufacturing and maintenance skills. For low cost turbine

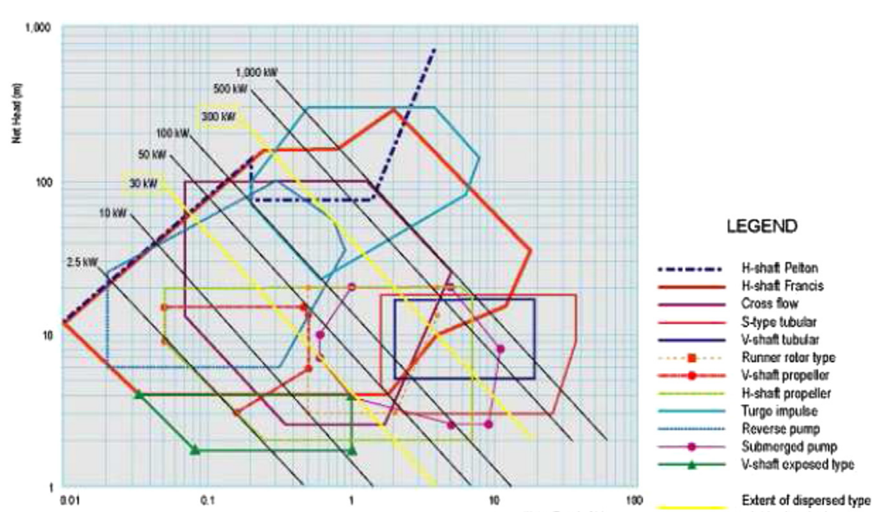

Fig. 9. Chart showing applicability of small scale hydropower turbines depending on head, flow and power [28].

that is to be locally manufactured Crossflow turbine should be considered.

(iii) Cost of generating unit power. The turbine that can give a high capacity factor should be favoured.

(iv) Performance of the turbine with respect to flow variation and water quality. Crossflow and Turgo turbines are applied in wide range of head and flow. In medium head-range with varied flow conditions, multi-jet Pelton turbine should be favoured. If water quality is poor (for example flow laden with sand and/or silt), impulse turbines such as Pelton, Crossflow and Turgo should be favoured.

(v) If the turbine must be located at some height above tailrace water level, a reaction turbine with a draft tube at the outlet should be favoured.

(vi) If flow can be maintained relatively constant, a pump-as-turbine should be considered.

When the 'right' turbine type has been identified for the site, the next step in turbine selection process is to estimate the turbine output power. To estimate the turbine output, Eq. (1) is used, rewritten in Eq. (5).

$$P_{output} = \eta_t \rho g H Q \tag{5}$$

The head (H) and flow (Q) are obtained from the site while density (ρ) and acceleration due to gravity (g) are constants. To estimate the power output of the identified turbine, the turbine efficiency (η_t) must therefore be determined. For the sake of estimates, the average value of turbine efficiency can be obtained from published values from small-scale turbine manufacturers or from organisations involved in MHP development. The values in Table 2 are recommended by the Japan International Cooperation Agency (JICA).

Table 2
Small-scale turbine types and their average efficiencies [28].

Turbine type	Turbine efficiency, η_t (%)
Pelton turbine	82
Crossflow turbine	77
Francis turbine	84
Propeller turbine	82
Tubular turbine	84

When the estimated turbine output power has been determined, then the applicable specific speed has to be estimated from the knowledge of site conditions such as head. Correlations between applicable specific speed and head can be used to estimate specific speed of the chosen turbine, such as those recommended by JICA, given in Table 3.

Table 3
Small-scale turbine types and their correlations for specific speed [28].

Turbine type	Applicable maximum specific speed N_{smax} in terms of head, H (m)
Pelton turbine	$85.49 \times H^{-0.213}$
Crossflow turbine	$650 \times H^{-0.5}$
Francis turbine	$\frac{2000}{(H+20)} + 30$
Horizontal-shaft Francis turbine	$3200 \times H^{-0.667}$
Propeller turbine	$\frac{2000}{(H+20)} + 50$
Tubular turbine	$\frac{2000}{(H+16)}$

The other important design parameter is the turbine rotational speed, which can be estimated from the knowledge of estimated power output, head and specific speed, using Eq. (4). It is important for MHP projects to select the turbine rotational speed that is equal to the synchronous speed for the standard generator. Synchronous speed N_f is given by $N_f = \frac{2 \times 60 \times \text{frequency}}{\text{No of poles}}$ and depending on the recommended frequency for the country, a list of possible values of synchronous speeds corresponding to various number of poles can be calculated, such those listed in Table 4. The design rotational speed of the turbine then becomes the synchronous speed that is close to the estimated rotational speed (from Eq. (4)).

Once the design turbine rotational speed has been selected, then it is important to recalculate the specific speed (using the new design turbine rotational speed). This is to check whether the specific speed of the selected turbine is within the acceptable range of that geometrically similar turbine. Table 5 can be used as a reference on the acceptable ranges of specific speeds for the geometrically similar turbines. If the calculated specific speed is not within the acceptable range, then another type of turbine should be tried (identified from manufacturers 'envelops').

The systematic process of selecting the optimum turbine according to the site conditions as presented in this section is summarised in terms of the a flow diagram in Fig. 10.

The process of turbine selection can be used to identify suitable turbines for the already identified MHP potential sites that are recorded in the national MHP inventory. The technical and economic details on the identified turbines can enrich the inventory with information that can be relevant to developers and other stakeholders.

4. Conclusions

Small hydropower, mostly defined as a hydropower system that has an installed capacity of less than 10 MW [55,15], is an important source of grid-based electricity worldwide [55]. As of 2013, a study conducted by UNIDO on status of small hydropower

Table 5
Range of speed number for the turbine type [28].

Turbine type	Range of specific speed
Pelton turbine	8–25
Crossflow turbine	90–110
Francis turbine	50–350
Propeller turbine	200–900
Tubular turbine	Greater than 500

Table 4
Different synchronous speed for a 50 Hz and 60 Hz generator.

Number of poles	Synchronous speed for 50 Hz	Synchronous speed for 60 Hz	Number of poles	Synchronous speed for 50 Hz	Synchronous speed for 60 Hz
4	1500	1800	14	429	514
6	1000	1200	16	375	450
8	750	900	18	333	400
10	600	720	20	300	360
12	500	600	24	273	327

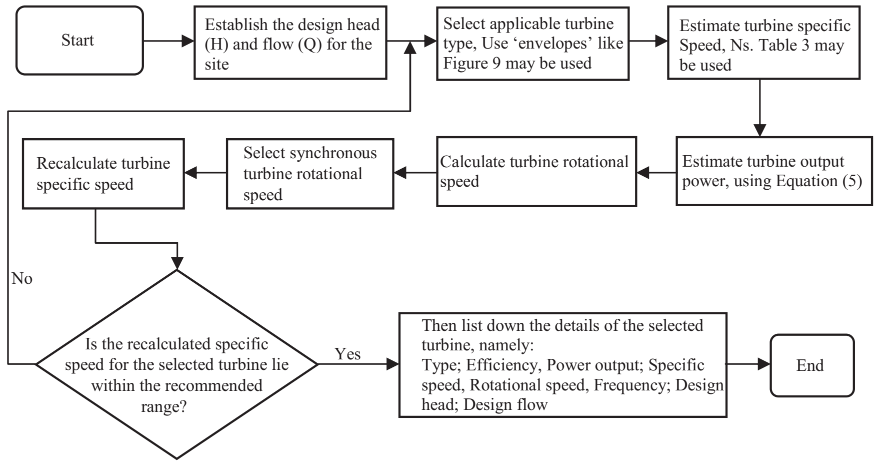

Fig. 10. A turbine selection process flow chart for the microhydropower project.

revealed that a worldwide proven potential of 173 GW exists and that about 75 GW has been installed [55]. However, the worldwide status of microhydropower, defined in this paper as those system with less than 100 kW installed capacity, is still unknown. MHP projects are shunned by most of the power utilities on the basis that power system of less than 100 kW is considered too small, economically, for grid-based electricity supply. MHP projects are therefore, mostly used as decentralised energy systems to supply power to off-grid communities. However, the resource potential for MHP is enormous in many countries [55]. Therefore, MHP systems can help to increase the national installed capacity if the generated electricity is fed into the grid, especially in developing countries. In particular, if the generated electricity is sold to the power utility company under the feed-in-tariff arrangement (for example), MHP can significantly contribute towards grid-based electricity supply. This can also help to create business opportunities for independent power producers.

This paper has come up with a comprehensive review and discussion on microhydropower technology. The technology is well matured, but it is not as popular as solar and wind energies in scholarly articles. From the discussions given in the paper, it can be concluded that microhydropower is a site-specific technology and that it involves different expertises during all stages of its development. The expertises required include surveyors, environmentalists, civil engineers, mechanical engineers and electrical engineers. Therefore, an inclusive project development team is required as well as acquisition of MHP knowledge by the team and stakeholders for successful popularisation of the technology.

For microhydropower projects, sometimes it is more economical to purchase an already manufactured turbine from off-the-shelf, than to design a specific turbine for the site. In this case, turbine selection for the site is an important exercise in the development of a microhydropower site. This paper has provided a comprehensive review on the commonly used turbines and it is hoped that the discussions therein provide further information on turbines' operating principles, construction characteristics and their optimum operating ranges. In addition, the paper has provided some factors to consider when selecting a turbine as well as a decision flow chart to help in systematic turbine selection for the site.

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